

## COMPRESSOR SURGE PREVENTION VIA DISTINCT BLADE SHAPES

### FIELD OF THE INVENTION

**[0001]** The present invention relates to impellers for compressors and pumps and the like, and more particularly, to an improved blade design for an impeller.

### BACKGROUND OF THE INVENTION

**[0002]** Impellers are widely used in a variety of applications to compress a fluid. For example, impellers are often used in air compressor applications for use in generating compressed air to power pneumatic tools and the like. Alternatively, impellers are used to compress a fluid for use in a pressurized system such as in supplying a pressurized fluid stream for use on a fire truck or pumping station. Further yet, such impellers are commonly used in the design and operation of aircraft engines, whereby a compressed fluid stream is provided via an impeller to propel an airplane in a desired direction. In any of the foregoing applications, it is desirable to provide an impeller capable of operating under varying flow conditions to provide a continuous supply of pressurized fluid, regardless of external forces.

**[0003]** As can be appreciated from the foregoing discussion, impellers are operable to compress a fluid stream for use in a plurality of applications. As previously discussed, one such application is an air compressor. Conventional compressors typically include an impeller, a diffuser, and a volute, whereby the

diffuser is in fluid communication with both the impeller and the volute and is operable to transfer a compressed air stream from the impeller to the volute for use in an external system. The impeller commonly includes a plurality of blades that are operable to receive and compress an external air stream between a hub of the impeller and a stationary shroud. Specifically, the impeller captures the external air stream at an inducer disposed proximate to a leading edge of each blade such that the captured mass air flow is forced between the hub and the stationary shroud through rotation of the impeller. The inducer is generally operable to capture the external air stream and force it between the hub and the stationary shroud as the impeller is rotated due to the generally curved or arcuate shape of the leading edge of each blade.

**[0004]** As can be appreciated, as the air stream travels between each of the blades, the shape of the shroud and hub are such that the air stream is compressed prior to reaching the volute. The compressed air stream is received into the volute for distribution into an external application such as a pneumatic tool or a vehicle engine or a fuel cell power module. The diffuser commonly includes a plurality of stationary vanes which are operable to diffuse the air stream and, thus, increase the static pressure of the compressed air. Such increases in static pressure generally increase the pressure of the air stream, thereby providing a desired output of pressurized air from the compressor. The stream is then collected and delivered to the exhaust system, via the volute.

**[0005]** In compressor design, it is increasingly important to deliver a constant stream of pressurized air to ensure proper operation of an external

device. As can be appreciated, interruption of a compressor can cause external devices, such as pneumatic tools, to seize and abruptly stop working. A common occurrence of such compressor failure is caused by surge. Surge is a term which generally refers to a condition caused by a significant reduction in pressure of an inlet air stream to an impeller. More particularly, surge is caused by flow separation at a suction side of each blade, generally near the leading edge. Such flow separation occurs at reduced flows when the incidence angle is large and the mass flow rate of air is reduced. Under such conditions, flow separation of the inlet air stream can cause a stalled flow to be received by the impeller, thereby causing the impeller to stall or fail.

**[0006]** In one application, an impeller is used with a compressor to deliver a constant supply of compressed hydrogen and oxygen to a vehicle engine to thereby power the engine. As can be appreciated, different operating conditions of the vehicle may cause varying inlet flow conditions. For example, the vehicle system may require more or less flow under different operating conditions such as weather changes, elevational changes, or system loads. In such an application, prevention of surge provides the vehicle with the ability to operate under such varying conditions, regardless of the varying inlet flow conditions.

**[0007]** Conventional systems attempt to treat surge by providing mechanisms operable to detect a reduced flow such that the system may stall or hinder the impending surge. Such conventional systems include positive displacement compressors with low performance and high noise levels,

compressors with modified casings or housings operable to delay the onset of stall, and variable geometry inlet guide vanes. In each of the foregoing systems, a significant amount of power is wasted driving a very unsteady or stalled flow without actually preventing surge. In this manner, conventional systems suffer from the disadvantage of requiring multiple systems to delay the onslaught of surge, thereby increasing the complexity and cost of the overall system without actually preventing surge. Additionally, because conventional systems merely delay the onslaught of surge, such conventional systems are unable to provide a constant stream of pressurized fluid as such systems are unable to perform under reduced flow conditions.

**[0008]** Therefore, an impeller which is capable of performing under reduced flow conditions, even as a net mass inlet flow is approaching zero, is desirable in the industry. Additionally, an impeller having a plurality of blades that are able to organize a would be stalled flow into a cohesive flow, while concurrently providing a blade structure that is readily and easily manufactured with a minimal number of components, is also desirable.

#### SUMMARY OF THE INVENTION

**[0009]** Accordingly, the present invention provides a compressor including a vaneless diffuser, a volute in fluid communication with the diffuser, and an impeller operable to compress a fluid stream and direct the fluid stream to the diffuser. The impeller includes a hub having an axis of rotation and a plurality of blades extending therefrom. The blades include a surface defined by an axial

direction (Z), a radius (R) defined from the axis of rotation, and a polar angle ( $\Theta$ ), whereby  $\Theta$  is substantially defined by the following equation:

$$\Theta = a * [\text{natural logarithm of } (R)] + b.$$

**[0010]** The impeller is operable to capture an air stream near a leading edge of each blade and compress the air stream for use in an external system. By defining each blade shape as a function of (R) only, the impeller is capable of functioning under conditions where inlet mass flow is at, or approaching, zero, and is therefore operable to prevent surge.

**[0011]** Further areas of applicability of the present invention will become apparent from the detailed description provided hereinafter. It should be understood that the detailed description and specific examples, while indicating the preferred embodiment of the invention, are intended for purposes of illustration only and are not intended to limit the scope of the invention.

#### BRIEF DESCRIPTION OF THE DRAWINGS

**[0012]** The present invention will become more fully understood from the detailed description and the accompanying drawings, wherein:

**[0013]** FIG. 1 is a perspective view of an impeller in accordance with the principals of the present invention;

**[0014]** FIG. 2 is a cross-sectional view of the impeller of FIG. 1;

**[0015]** FIG. 3 is a more detailed cross-sectional view of the impeller of FIG. 1;

**[0016]** FIG. 4 is a partial perspective view of the impeller of FIG. 1 showing a meridional profile of an impeller blade;

**[0017]** FIG. 5 shows the impeller of FIG.1 incorporated into a collecting assembly;

**[0018]** FIG. 6 is a meridional view of an impeller blade for use with a radial impeller;

**[0019]** FIG. 7 is a meridional view of an impeller blade for use with a mixed-flow impeller;

**[0020]** FIG. 8 is a graphical representation of a compressor performance map showing a classical surge line; and

**[0021]** FIG. 9 is a schematic diagram showing a compressor in accordance with the principals of the present invention.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

**[0022]** The following description of the preferred embodiments is merely exemplary in nature and is in no way intended to limit the invention, its application, or uses.

**[0023]** With reference to the figures, an impeller 10 is provided and includes a hub 12 and a plurality of blades 14 radially extending therefrom. The impeller 10 is operable to capture an air flow through cooperation between the plurality of blades 14 and the hub 12 to compress the air flow and deliver a pressurized air stream as the impeller 10 rotates about a central axis of rotation 16.

**[0024]** With reference to FIG. 1, the impeller 10 is shown to include a generally circular shape having the hub 12 disposed coaxially with the axis of rotation 16. The hub 12 includes a tip 18 and a hub contour 20 formed proximate each blade 14, as best shown in FIGS. 2 and 3. The hub tip 18 includes a generally arcuate surface 22 for distributing a received air flow to each of the plurality of blades 14.

**[0025]** With reference to FIG. 4, the blades are shown to include a generally sweeping arcuate surface extending radially and axially from the hub 12. As can be appreciated, the sweeping nature of the arcuate surface 24 further provides each blade with an angular component  $\Theta$ , generally referred to as the polar angle. In this manner, the overall shape and contour of each blade 14 is defined as a function of an axial direction (Z), a radius (R), and the polar angle ( $\Theta$ ). The axial direction (Z) generally dictates the overall height of each blade 14 and extends in a direction generally perpendicular to the axis of rotation 16 of the hub 12. The radial direction, or radius (R), extends outwardly from the central axis of rotation 16 to generally define a length of each blade 14. In this manner, each blade 14 includes a leading edge 26 extending along the axial direction (Z) and a trailing edge 28 formed generally at a distal end of each blade 14 along the radial direction (R), as best shown in the meridional projection of FIG. 4. Additionally, each blade 14 includes a tip contour 27 extending between the leading edge 26 and the trailing edge 28 for interaction with an air stream, as will be discussed further below.

**[0026]** As previously discussed, each blade 14 includes a sweeping arcuate surface 24 generally defined by an axial direction (Z), a radial direction (R), and an angular direction or polar angle ( $\Theta$ ). As can be appreciated, as each blade 14 moves away from the hub 12, the angular position at any given radial value (R) will vary. In other words, the angular position, or polar angle ( $\Theta$ ), is defined as a function of the radius (R) by the following equation:

$$\Theta = a * [\text{natural logarithm of } (R)] + b.$$

**[0027]** The "a" and "b" terms in the above equation are constants and depend on a required flow that the impeller 10 must capture at a given rotational speed. Such constants are generally governed by the overall requirements of the impeller 10 and are often dictated by the particular application in which the impeller 10 is used. In this manner, regardless of impeller 10 rotational speed, mass air flow, or pressure rise through the impeller 10, the blade polar angle ( $\Theta$ ) is only determined as a function of the radius (R). Each blade 14 includes a generally constant shape extending in the axial direction (Z) due to the polar angle being formed as a function of radius (R), as best shown in FIGS. 1 and 4.

**[0028]** By way of example, FIG. 4 depicts a blade having a shape according to the principles of the present invention. The location of points A<sub>1</sub> and A<sub>2</sub> along the blade 14 are defined by the polar angles  $\Theta_1$  and  $\Theta_2$ , respectively and radii R<sub>1</sub> and R<sub>2</sub>, respectively. As described, the particular location of  $\Theta_1$  is generally defined as  $\Theta_1 = a * [\text{natural logarithm of } (R_1)] + b$  while  $\Theta_2$  is generally defined as  $\Theta_2 = a * [\text{natural logarithm of } (R_2)] + b$ . In this regard, the overall blade shape is defined as a function of the polar angle ( $\Theta$ ) along the length of the



blade 14 at a particular radial (R) position. While two angular positions (i.e.  $\Theta_1$  and  $\Theta_2$ ) are depicted, it should be understood the overall blade shape could be defined by an infinite number of polar angles extending between the leading edge 26 and the trailing edge 28 at respective radial positions, and should be considered within the scope of the present invention. Such a relationship provides for improved manufacturability as upper and lower die molds may be quickly separated upon forming the impeller 10. As can be appreciated, a blade 14 defining a surface as both a function of (R) and (Z) increases manufacturing complexity as part removal from the die is restricted by the extension of the blade 14 in both the radial (R) and axial (Z) directions. Furthermore, by defining blade shape as a function of only radius (R), impeller 10 performance is greatly improved as inlet mass flow and pressure are reduced, as will be discussed further below.

**[0029]** With reference to FIG. 5, the impeller 10 is shown incorporated into a collecting assembly 30 which includes a vaneless diffuser 34 and a volute 32. The vaneless diffuser 34 radially surrounds the impeller 10 and defines a generally open space 38 disposed proximate the volute 32. The volute 32 radially surrounds an outer diameter of the diffuser 34 and similarly includes an open space 36. The open space 36 of the volute 32 is in fluid communication with the open space 38 of the vaneless diffuser 34. In this manner, the impeller 10 is operable to transmit a compressed fluid to the volute 32 via the open space 38 of the diffuser 34.

**[0030]** In operation, the impeller 10 receives a mass flow of air at an inlet or inducer generally proximate the leading edge 26 of each blade 14. As the leading edge 26 captures the air flow through rotation of the impeller 10 about the central axis 16, the air is redirected into the impeller 10 by leading edge 26 and contour of each blade 14. Once the air flow is captured by the blades 14, the air is forced to travel along the arcuate surface 24 and tip contour 27 of each blade 14, generally between the hub contour 12 and an external structure such as a stationary shroud 40 (best seen in FIGS. 2 and 3). Movement of the air along the blades 14 from the leading edge 26 to the trailing edge 28 causes the air stream to increase pressure due to the overall shape of each blade 14, confined space between each blade 14 and stationary shroud 40, and the overall rotational speed of the impeller 10.

**[0031]** Once sufficient pressure is achieved, the air stream is released into the open space 38 of the vaneless diffuser 34 for collection. As can be appreciated, each impeller blade 14 forms an opening 42 between each pair of respective blades 14 for interaction with the diffuser 34. Specifically, the openings 42 are in fluid communication with the open space 38 of the diffuser 34 and serve to deliver the compressed air stream to the open space 38 for collection and distribution to the volute 32. Upon receiving the compressed air stream, the volute 32 distributes the fluid stream to an external source such as a vehicle engine, fuel cell, or pneumatic tool (neither shown) via an outlet 44.

**[0032]** In one embodiment, the impeller 10 is a radial impeller, whereby a mass flow of air received at the leading edge 26 of each blade 14 travels along

the blade 14 between the leading edge 26 and the trailing edge 28 for compression, as previously discussed. Such an arrangement serves to compress air through a centrifugal method, whereby the air stream is captured by the inducer at the leading edge 26 generally in the axial direction (Z) of each blade 14. Once captured, the air flow is caused to travel along the arcuate surface 24 of each blade generally in the radial (R) direction through rotation of the impeller 10, as best shown in FIG. 6 and indicated by a plurality of arrows 15. In such a relationship, high pressure air flow can be achieved, as the full force of the air is directed in a single direction (R).

**[0033]** In such a radial impeller 10, the length of the inducer, or height of the leading edge 26 in the axial direction (Z), should be within 5 to 7% of the outer diameter of the impeller 10 for optimum impeller performance, as will be discussed further below.

**[0034]** In an alternate embodiment, the impeller 10 is a mixed-flow impeller, as shown in FIG. 7. In view of the similarity between the radial impeller 10 and the mixed-flow impeller, like reference numerals are used hereinafter and in the drawings to identify like components while like reference numerals containing letter extensions are used to identify those components that have been modified.

**[0035]** In a mixed-flow impeller, an entering air flow enters along the axial direction (Z), but does not exit the impeller 10 solely in the radial direction (R). Rather, in a mixed-flow impeller application, a compressed air stream exits the impeller in both the axial (Z) and radial (R) directions, as best shown in FIG. 7 and indicated by a plurality of arrows 17. In such systems, the impeller includes a

plurality of blades 14a having a leading edge 26a, a trailing edge 28a, and a blade contour 27a extending therebetween, as best shown in the meridional view of FIG. 7. Additionally, such blades 14a further include a hub contour 20a having a rapid area reduction 46 disposed generally  $1/3$  the overall length of the blade 14a from the leading edge 26a, whereby the overall length of the blade 14a is measured between the leading edge 26a and the trailing edge 28a, as best shown in FIG. 7.

**[0036]** The rapid area reduction 46 is formed as a function of the overall area of the leading edge 26a. Specifically, the reduced area 46 in the axial direction (Z) should be within  $2/3$  to  $3/4$  of the area of the leading edge 26a for optimum performance, as will be discussed further below. In this manner, the rapid area reduction 46 includes a starting point at a distance "X" away from the leading edge 26a and extends from such point to the trailing edge 28a of each blade 14a, as shown in FIG. 7. As previously discussed, the distance "X" is roughly equal to the following equation:  $X = 1/3 * (\text{the total length of the blade})$ .

**[0037]** In any of the foregoing embodiments, proper operation of the impeller 10 hinges on the ability of the impeller 10 to receive an air stream and compress such air stream to consistently deliver a predetermined fluid pressure for use in an external system. In this manner, the impeller 10 must be able to consistently compress a fluid stream, regardless of the condition of the input fluid stream. In doing so, the impeller 10 must be able to function under minimal input flow characteristics to avoid the onslaught of surge.

**[0038]** As previously discussed, surge is caused by flow separation on a suction surface, or near the leading edge 26, of the impeller blades 14 and occurs

at reduced flow when the incidence angle is large. Surge can cause failure of the impeller 10 as such flow separation produces a "stalled" or separated flow. FIG. 8 is a graphical representation of a surge line indicating a point at which a stalled flow is experienced at a given rotational speed.

**[0039]** As mass flow rate and pressure of a received air stream are reduced, an impeller 10 is likely to experience surge. Speed curves 48, indicated in FIG. 8, can be drawn for varying rotational speeds of the impeller 10, whereby each speed curve 48 intersects a surge line (A-B) at a point at which a stalled flow occurs. The point at which the speed curve 48 contacts the surge line (A-B), is the point at which the impeller 10 will experience surge for a given rotational speed. As can be appreciated, as the pressure ratio and mass flow rate of an input fluid stream are reduced, the likelihood of surge is increased.

**[0040]** With continued reference to FIG. 8, it is shown that surge can be prevented if the surge line (A-B) is coaxially aligned with the vertical axis such that the pressure ratio is finite and mass flow rate is zero, thereby preventing surge. Such a relationship is graphically indicated in FIG. 8 by extending the speed lines to the vertical axis using dashed lines 50 and coaxially aligning the surge line (A-B) with the vertical axis. By doing so, the impeller 10 may operate under a condition where the pressure ratio is finite and mass flow rate is zero, thereby preventing the occurrence of surge.

**[0041]** In operation, the impeller 10 of the present invention is operable to prevent surge by re-attaching the separated flow and allowing a useable input fluid stream. In other words, the blade shape is designed to stabilize the "would be

stalled" flow such that the flow remains attached to the blade surface 24 at all flows, even under conditions where the flow is reduced to zero.

**[0042]** To ensure that a received fluid stream remains attached to the impeller blades 14 under any input flow condition, three elements must be met. First, the shape of the blade 14 must only be a function of the radius (R). In sum, the polar angle ( $\Theta$ ) should substantially satisfy the following equation:  $\Theta = a * [\text{the natural logarithm of } (R)] + b$ , as previously discussed. By generally meeting the above equation, it should be understood that it is intended that minor variations would similarly eliminate surge.

**[0043]** A second requirement to achieve surge prevention is that a vaneless diffuser 34 should be used in conjunction with the impeller 10. In other words, a diffuser 34 having an open space 38 should be used in conjunction with the impeller 10 and should not include a plurality of fixed vanes.

**[0044]** For a radial impeller 10, the third requirement in the prevention of surge is that the length of the inducer, or height of the leading edge 26 in the axial direction (Z), should be within 5% to 7% of the outer diameter of the impeller 10 for optimum performance, as previously discussed and best shown in FIG. 6.

**[0045]** In the case of a mixed-flow impeller, the third requirement to prevent surge is that the area of the rapid area reduction 46 in the axial direction (Z) should be within 2/3 to 3/4 of the area of the leading edge 26a. In this manner, the reduced area 46 begins at a distance "X" away from the leading edge 26a of

the blade 14a and extends from such beginning point to the trailing edge 28a of each blade 14a, as previously discussed and shown in FIG. 7.

**[0046]** With reference to FIG. 9, a compressor 100 is provided and is operable to compress an air stream for use in an external system 102. The compressor 100 is rotatably driven by a motor 104, having a shaft 106 extending therebetween. The impeller 10 is disposed within the compressor 100 and is operably engaged with the shaft 106. Specifically, the shaft 106 is operably connected to the hub 12 of the impeller 10 such that rotation of the shaft 106 concurrently rotates the impeller 10. As previously discussed, rotation of the impeller 10 causes the leading edge 26 of each blade 14 to capture an inlet air flow and deliver a compressed air stream to the collecting assembly 30. Upon sufficient compression, the collecting assembly 30 is operable to deliver the compressed fluid to the external system 102 via outlet 44, as previously discussed.

**[0047]** As can be appreciated, such a relationship between a vaneless diffuser 34 and an impeller blade 14, having a surface defined only as a function of radius (R), can be applied to any range of applications and is not merely limited to a compressor. Furthermore, such an impeller 10 is not limited to compression of air and may be applied in any system requiring a compressed fluid such as, but not limited to, a compressed stream of water or hydrogen. In any of the foregoing applications, prevention of surge provides the particular application with the ability to consistently produce and maintain a stream of pressurized fluid under any external or input flow conditions.

**[0048]** The description of the invention is merely exemplary in nature and, thus, variations that do not depart from the gist of the invention are intended to be within the scope of the invention. Such variations are not to be regarded as a departure from the spirit and scope of the invention.